INVESTIGATION OF CUTTING TEMPERATURE AND CUTTING FORCE FROM MIST FLOW PATTERN IN MQL TECHNIQUE

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DEDICATION

Especially dedicated to my beloved family Appa, Amma, Julie, Charles, Dinisha and loving husband, Andrew Selvaraj and also for my helpful supervisors Associate Professor Dr. Erween bin Abd Rahim and Associate Professor Dr. Norzelawati binti Asmuin and friends, I will always keep all of you in my mind.

In my deepest gratitude and thoughtfulness

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ABSTRACT

Minimum Quantity Lubrication (MQL) is an alternative method to supply the cutting fluid in the formation of mist. MQL has proven to reduce machining cost and increase machining performance. Previous research have stated that machining performance is affected by the lubricant type, flow rate, the distance between nozzle and tool tip, and the workpiece material. These important parameters are not reported in many research documents. MQL is known for its many benefits but no one was able to prove that the statement is true or ever suggested a systematic procedure to prove MQL's efficiency. The effectiveness and the working principle of MQL are still questionable with very few explanations provided. The present study is about investigation of cutting temperature and cutting force from mist flow pattern in MQL technique The MQL nozzle distance and cutting fluid flow pattern are among the factors that can provide optimum machining performance in term of cutting force and cutting temperature. The objective of this study is to conduct machining process using MQL technique with different combination of spray parameters and to optimize spray parameters for minimum machining temperature and cutting forces. The four nozzle distances of 3, 6, 7 and 9 mm were selected based on the results obtained from *Phase Doppler Anemometry* (PDA). The machining performance was evaluated under three levels of cutting speed and two levels of feed rate at constant depth of cut. The cutting force was measured using a set of dynamometer and cutting temperature using thermal imager. The most suitable mist flow pattern during machining was the largest spray cone angle supplied under 0.4 MPa input air pressure. The results obtained from the machining process shows a significant reduction of cutting force and cutting temperature at the nozzle distance in the range of 6 to 9 mm under 0.4 MPa input air pressure for larger diameter OD_{30} nozzle.

ABSTRAK

Pelinciran Kuantiti Minimum (MQL) adalah satu kaedah alternatif untuk membekalkan cecair pemotongan dalam pembentukan kabus. MQL telah terbukti untuk mengurangkan kos pemesinan dan meningkatkan prestasi pemesinan. Kajian sebelum telah menyatakan bahawa prestasi pemesinan dipengaruhi oleh jenis minyak pelincir, kadar, jarak antara muncung dan hujung alat, dan bahan bahan kerja mengalir. Parameter penting yang tidak dilaporkan dalam dokumen penyelidikan. MQL dikenali dengan banyak manfaat tetapi tiada yang dapat membuktikan bahawa kenyataan itu adalah benar atau pernah mencadangkan satu prosedur yang sistematik untuk membuktikan kecekapan MQL ini. Kajian ini adalah mengenai penyiasatan suhu pemotongan dan kuasa pemotongan dari corak aliran kabus dalam teknik MQL Jarak muncung dan memotong corak aliran bendalir adalah antara faktor yang boleh memberikan prestasi pemesinan optimum dari segi daya pemotongan dan suhu pemotongan. Objektif kajian ini adalah untuk menjalankan proses pemesinan menggunakan teknik MQL dengan kombinasi parameter semburan yang berbeza. Selain itu, ujikaji ini juga bertujuan untuk mengoptimumkan parameter semburan bagi suhu pemesinan minimum dan daya pemotongan. Empat jarak muncung iaitu 3, 6, 7 dan 9 mm telah dipilih berdasarkan kepada keputusan yang diperolehi daripada *Phase Doppler Anemometry* (PDA). Prestasi pemesinan dinilai di bawah tiga tahap kelajuan pemotongan dan dua tahap kadar suapan pada kedalaman pemotongan 0.2 mm. Daya pemotongan telah diukur dengan menggunakan dinamometer manakala suhu pemotongan menggunakan pengimejan terma. Didapati bahawa sudut semburan yang besar yang dihasilkan pada tekanan udara 0.4 MPa menghasilkan corak aliran kabus yang paling sesuai untuk pemesinan. Keputusan bagi OD_{30} menunjukkan bahawa daya dan suhu pemotongan pada jarak muncung sekitar 6 hingga 9 mm pada tekanan udara 0.4 MPa dapat dikurangkan.

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ABBREVIATIONS

V_c	-	Cutting speed
f_r	-	Feed rate
d	-	Depth of cut
F_c	-	Cutting force
T_c	-	Cutting temperature
mm	-	milimeter
µm	-	micrometer
P_{inj}	-	Injection pressure
MQL	-	Minimum quantity lubrication
STP	-	Spray tip penetration
PDA	-	Phase Doppler Anemometry
SMD	-	Sauter mean diameter
MMD	-	Mass mean diameter
NC	-	Numerical Control
WC	-	Tungsten carbide
Co	-	Cobalt
OD_{25}	-	Nozzle with outlet diameter of 2.5 mm
OD_{30}	-	Nozzle with outlet diameter of 3.0 mm
i	-	Denote size range considered
N_i	-	The number of drops in size range i
D_i	-	The middle diameter of size range i

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Machining or metal cutting process is one of the common manufacturing processes used to remove an unwanted material to achieve desirable shape and specific geometry and dimension in the production of mechanical components. The three most widely used cutting operations are turning, milling and drilling. Turning is a most commonly employed process by using a single point tool that removes unwanted material to produce a surface of revolution by holding the tool rigidly in a tool post and moved at a constant rate along the axis of the bar, cutting away a layer of metal to form a cylinder or a surface of more complex profile (Shaw, 2005).

Machining process is greatly influenced by cutting fluid which is used to reduce the heat generated during machining process. Water was the first cutting fluid used in machining process and was replaced with other fluids as more studies done on the ability of water to perform as cutting fluid. Cutting fluid is widely used in machining process due to its ability to cool, lubricate and to convey the chips away from the cutting zone. As a result, it improves the tool life, protects the workpiece and tool from corrosion, improve surface finish and dimension accuracy of a product. Cutting fluid had acquired sufficient and proved to be necessary adjunct in high speed machining of difficult material such as the exotic steels and specially alloyed nonferrous metals. As the new methods of machining are constantly being developed, the cutting fluid industry provided machinist with a choice of several cutting fluid. Straight mineral oils, combinations of mineral oils and vegetable oils, animal fats, marine oils, mixes of free sulphur and mineral oil are commonly used as cutting fluids and suds (Byers, 2006).

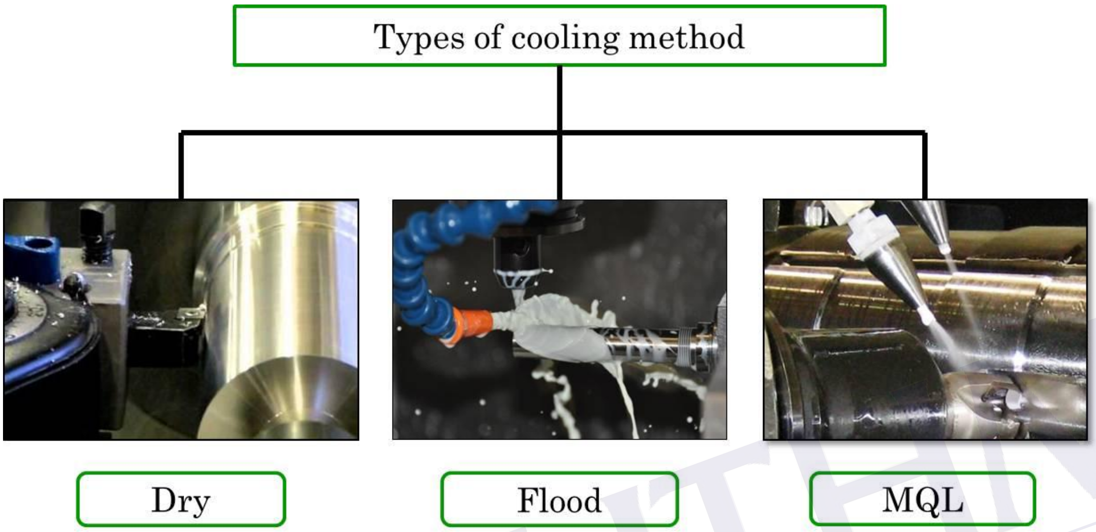

Figure 1.1: Types of cooling method in machining process

Several techniques as shown in Figure 1.1 have been developed in recent years for controlling the temperature in the cutting zone in order to increase the overall effectiveness of the cooling process during the machining process. Dry machining is one of the methods introduced as a new way to reduce the environment pollution. No cutting fluids are supplied during the machining process under dry machining, but this method cannot be applied in all machining process due to some constraint. Not all the materials can be machined without cutting fluids and machining under dry condition reduces tool life and affects the finishing process due to high heat generation. Flood coolant method has been used extensively since cutting fluid was introduced in the machining industry. Cutting fluid is delivered excessively to cool and lubricate the cutting tool and workpiece subsequently reduces the heat generated at the tool-chip interface. With the rapid growth in the machine tool industry and the rising awareness of environmental and health issues leads to near dry cutting (Obikawa *et al*., 2008). Near dry cutting also known as minimum quantity lubricant (MQL) is another method of cooling. In MQL method a small amount of cutting fluid is carried by air jet directly to the cutting zone. The mists are produced under the atomization process and are supplied to the cutting zone (Obikawa *et al*., 2006). The lubricant is directly sprayed into the tool-chip interface thus guarantees a good level of lubrication (Attanasio *et al*., 2005). The chip produced is flushed away from the cutting zone due to the action of compressed air. The machined surface is almost completely dry after machining process. The compress air not only contributes in transporting the oil particles, but it also helps in the cooling and chip removal process. The heat produced during cutting is removed by the injected air and the evaporation of the cutting fluid. The remaining cutting fluid vaporizes due to the high machining temperature. The high pressure jet cutting fluid with tiny droplets of oils decreases the friction between chip and the rake face during machining process. The tiny oil droplets penetrate into chip-tool interface thus reduces the cutting temperature and improves tool life to some extent. (Dhar *et al*., 2006)

1.2 Problem Statement

Cutting fluid especially those containing oil have become a huge liability since Environmental Protection Agency (EPA) have classified them as hazardous wastes to the environment and human health. The application, maintenance and its disposal are high thus increasing the machining cost. Improper disposal of cutting fluid can cause pollution and long term effects. As the increasing number of the environmental protection laws and regulations, a new method uses minimum quantity lubricant (MQL) has been applied to supply the cutting fluid in machining process.

MQL which is also referred as near-dry machining, an air-oil mixture fed onto the machining zone is a recently introduced technique in machining. MQL have been the most preferable choice in machining process due to its ability to reduce the coolant usage, safe environment and contribute the most in reducing machining cost, MQL process started to replace the flood coolant technique due to its ecological and fluid coolant benefits. Today, this method of lubricating is applied to other machining process such as drilling and milling. Some authors have estimated the total machining cost savings to be between 7 and 17 % (Duchosal *et al*., 2012).

From the previous research it was found that machining performance of cutting temperature and cutting force are affected by the lubricant type, flow rate, the distance between nozzle and tool tip, and the workpiece material. All these parameters are found to be dependent on the work material and process conditions. Only the appropriate oil quantity and appropriate distance between the nozzle and tool tip provides the optimum process condition. To achieve these, the correct amount of lubricant to be applied, type of lubricant to be used, the application method and the position of lubricant application should be considered. For example, it was assumed that the oil can penetrate the tool-workpiece interface due to high pressure of the compressed air that serves as a vehicle for the oil droplets. No comparison was made between the contact pressure at this interface and that of compressed air. These important parameters are not reported in many research documents and papers on near dry machining. Even though MQL is known for its many benefits but no one was able to prove that the statement is true or no one have ever suggested a systematic procedure to prove MQL's efficiency. Insufficient recommendations can cause difficulties to make proper choices of the equipment and parameter in machining. The effectiveness and the working principle of MQL are still questionable with very few explanations provided.

Meanwhile, the nozzle design and most preferable flow pattern have to be selected in order to achieve the best particle size for excellent penetration at chip-tool interface. The number of previous study on specific nozzle design and the best mist flow pattern are very limited thus it's difficult to explain how MQL have greater cooling ability than conventionally supplied metal working fluid. Thus selecting the best design for nozzle head, nozzle distance from the tool tip and most desirable flow pattern for generating the best particle size would be a difficult task. The purpose of this study is to select an appropriate nozzle distance in turning process to improve the cutting temperature and cutting force using MQL cooling method.

1.3 Objective of study

The specific objectives of this study are:

i. To conduct the machining process using MQL techniques with different combination of spray parameters.
ii. To optimize the spray parameters for minimizing the machining temperature and cutting forces.

1.4 Scope of study

The scopes of this study are:
i. Cemented carbide was used as the cutting tool.
ii. Mild steel AISI 1045 was used as the workpiece material.
iii. NC Harrison Lathe machine was used for machining process.
v. The study is based on the cutting parameter such as cutting speed, feed rate and depth of cut. These parameters are selected due to the easy control compare to other cutting parameters.
vi. Machining under MQL condition with selected parameter input air pressure 0.2, 0.3 and 0.4 MPa using nozzles with outlet diameter of 2.5 mm (OD_{25}) and 3.0 mm (OD_{30}).
vii. Phase Doppler Anemometry was used to measure the particle distribution and particle size under various input pressure
viii. Experiment parameters are; cutting speed, V_c = 100, 160 and 220 m/min, feed rate f_r = 0.15, 0.30 mm/rev, depth of cut, d = 0.2 mm.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

There are many important aspects need to be considered before the process can be executed. As the technology grows, many improvements has been introduced to increase the efficiency and to reduce the cost of machining. Cost reduction is contributed by many aspects in machining. For example, by enhancing the tool life the machining cost can be reduced indirectly. To prolong tool life, the cutting temperature generated during machining process must be reduced. The common method used would be by supplying cutting fluid during machining process. However, using cutting fluids have been reported to cause many health problems to the workers such as skin disease, lungs infections and breathing problems. And the improper disposal of the cutting fluids pollutes the environment. Moreover, the cost to recycle the cutting fluids is higher compare to the machining cost. Most of the chemically modified cutting fluids need to undergo many steps of treatment before being disposed. To overcome this problem, many researches have been directed towards in minimizing the use of the cutting fluids or to totally eliminate them (Sreejith, 2008). Machining in dry conditions is not always favourable since it has many constraints and high heat generation.

2.2 Coolant Method

The main functions of cutting fluids in machining processes are to cool, to lubricate and to make chip transport easier, to improve the tool life, the product surface finish and the dimension accuracy (Li *et al*., 2010). There are several types of cutting fluid delivery techniques applied in machining process. Conventional flood cooling applicant is a very common method of supplying cutting fluid in a stream flow to the tool-work interface. This method uses a large amount of cutting fluid during machining to reduce the heat generation. As an alternative to the conventional flood cooling method, minimum quantity lubrication (MQL) was introduced.

Cutting fluid is supplied in mist form under MQL method. This method is also known as near dry machining process which uses only ten to thousands of amount of cutting fluids used in flood cooling machining (Machado and Wallbank, 1997). This method was introduced to reduce the usage of cutting fluid which is the root to a high machining cost. Moreover, this method enables to reduce health problem among the workers and reduce environmental problems.

In other cases, machining was done without the use of cutting fluid and this method is called dry machining process (Groover, 2011). Naturally, a dry machining process is especially effective in reducing environmental damage (Yokota *et al*., 2014). However, not all materials can be machined easily under dry conditions. Dry machining is less effective when operating in higher machining efficiency, better surface quality and severe cutting condition is required (Dhar *et al*., 2006b). There are lot of constraint in dry machining and only few types of material can be machined using this method.

2.3 Minimum Quantity Lubrication (MQL)

Minimum quantity lubrication (MQL) or near dry machining is a very commonly used term in machining industry. Gaitonde (2008) refers to MQL in machining as an alternative to completely dry or flood cooling method, which has been considered as one of the solutions for reducing the amount of cutting fluid to address the environmental, economical and mechanical process performance concerns. The real explanation of MQL is a small amount of cutting fluid is mixed in the chamber with compressed air under the atomization process to produce small droplets of oil and air in mist form. In MQL, this fine mist containing oil droplet is being dispersed in a high velocity of air during machining process to the cutting interface. MQL refers to the use of cutting fluids of only a small amount of flow rate in the range of 50-500 ml/h. The amount of cutting fluid used in MQL method is about three to four orders of magnitude lower than the amount of cutting fluid used in flood cooling condition (Dhar *et al*. 2006b, Gaitonde, 2008, Thakur, 2009). Less cutting fluid were used during machining with more effective results in the reduction of cutting force and cutting temperature. MQL also provide good job satisfaction by reducing machining cost and creating clean and easy to handle working place.

2.3.1 Working principle and Delivery Method

The small quantity of cutting fluid is often supplied to the cutting interface via the nozzle in the tiny droplets form. An atomizer blends the cutting fluid with high velocity of compressed air. The atomizer will convert the bulky liquid into mist and fog. Normally, the formation of droplet size ranging from 1 to 5 µm and it seems invisible due to their tiny size. However, the oil mist smaller than 10 µm in diameter may cause lung disease. The floating mist can be easily penetrated into the lungs and cause health problem such as breathing difficulties and lungs cancer (Obikawa *et al*., 2009). Therefore, it is very important to spray an aproperiate amount of oil mist to the tool-chip interface.

In most cases, the mist is formed at the nozzle throat around the discharge outlet of the nozzle. Both oil and compressed air were blended together to create tiny particle size. On the other hand, atomizer chambers were used to produce mist. The mist was supplied to the tool-workpiece interface using external and internal nozzles. Figure 2.1 shows the external nozzle used to supply cutting fluid during turning process (Dhar *et al*., 2011). The coolant used was straight run cutting oil (VG 68) at a flow rate of 60 ml/hr. The oil pressure was set at 2 MPa (20 bar) and the air pressure was 1.5 MPa (15 bar).

Meanwhile, Obikawa *et al*. (2009) used internal nozzle to supply cutting fluid to the edge of the cutting insert as shown in Figure 2.2. Small oil hole with the outlet diameter of 1.2 mm was drilled through in the tool holder from the bottom. A very small amount of oil dispensed at a time was mixed and stirred with compressed air at the inlet of an oil hole in a tool holder. The oil mist was then sprayed with the compressed air from only an outlet of a nozzle on the side of tool flank face.

Figure 2.1: External nozzle in turning process (Dhar *et al*., 2011)

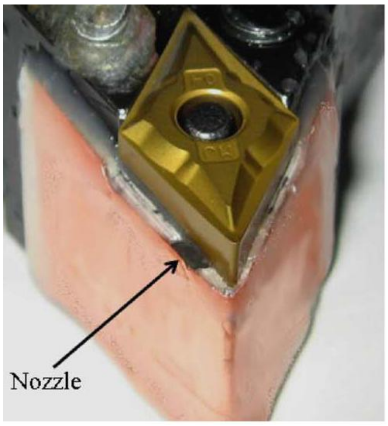

Figure 2.2: Internal nozzle design (Obikawa *et al*., 2009)

2.3.2 MQL Droplets and Distribution

The process of generating drops is called atomization. The process of atomization begins by forcing the liquid through a nozzle. The potential energy of the liquid was measured as liquid pressure for hydraulic nozzles or liquid and air pressure for two-fluid nozzles. This potential energy of the liquid along with the geometry of the nozzle causes the liquid to emerge as small ligaments. These ligaments are then break up further into very small "pieces", which are usually called drops, droplets or liquid particles as shown in Figure 2.3.

Each spray provides a range of drop sizes or diameter. This range is referred to as a drop size distribution. A simple explanation of this process is the breakup of liquid as it emerges from an orifice. Various spray nozzles have different shape of orifices and produce various spray patterns such as hollow cone, full cone and flat spray as shown in Figure 2.4. The drop size distributions are dependent on the nozzle type and vary significantly from one type to another. Other factors such as the liquid properties, nozzle capacity, spraying pressure and spray angle can affect the drop size as well (Schick, 2006, Rashid *et al*., 2012).

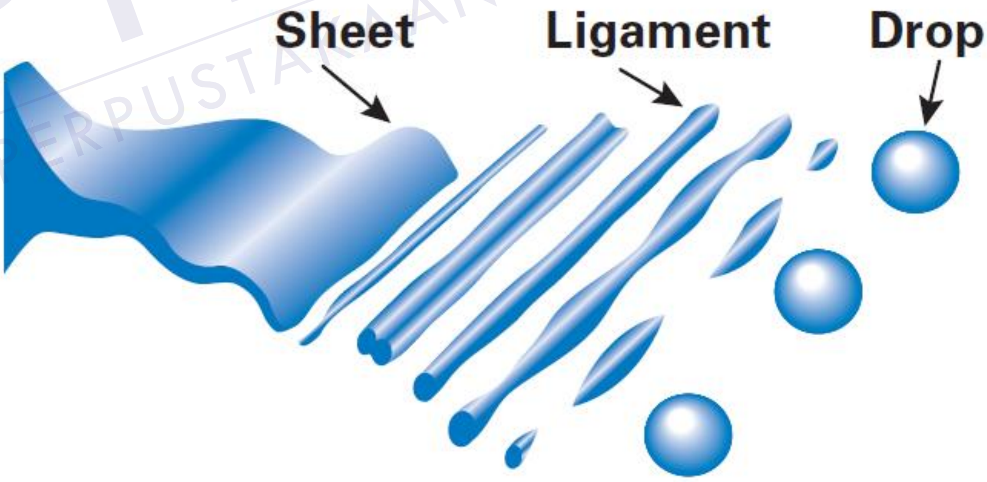

Figure 2.3: Atomization process (Schick, 2006)

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